Development of Global Heat and Freshwater Anomaly Analyses

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Project Summary:

Understanding global climate variability requires knowledge of ocean temperature and salinity fields (or more precisely ocean heat and fresh water content). Accurate estimates of changes in distribution of ocean heat and fresh water content combined with an analysis of how thermohaline (temperature-salinity) anomalies enter, circulate within, and leave the ocean is necessary to monitor and understand interannual to decadal changes in climate. Such fields and analyses help to verify climate models and improve their predictive skill. They help to diagnose the components of sea level change (ocean temperature variations versus ocean mass variations).

This project is developing, updating, and analyzing global analyses of ocean temperature and salinity using quality-controlled compilations of in situ temperature and salinity data from eXpendable Bathy Thermographs (XBTs), shipboard Conductivity-Temperature-Depth (CTD) measurements, CTD-equipped autonomous profiling floats (Argo), moored buoys, and other sources. These data are used to estimate global ocean temperature and salinity fields, hence ocean heat and freshwater content variations on annual time-scales. Historically, in situ data distributions are relatively sparse, especially before the advent of Argo. However, variations in ocean heat content are closely related to variations ocean sea-surface height, which has been very well measured since late 1992 by satellite altimeters. By exploiting this close relationship, we are able to quantify sampling errors inherent in estimating a global average of upper ocean heat content from an incomplete data set. We can also exploit the relationship to improve maps of ocean heat content from in situ data by using the altimeter data with local correlation coefficients applied as a first guess at upper ocean heat content in poorly measured regions.

This project, a part of the NOAA Office of Climate Observations Ocean Observing System Team of Experts, by providing analyses of ocean data, helps NOAA to use and assess the effectiveness of the sustained ocean observing system for climate. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory by the PMEL and JIMAR investigator, but in very close consultation with the co-investigator at NASA's Jet Propulsion Laboratory.

Project Accomplishments:

In FY2007 a good deal of effort was expended on identifying one set of instrument errors, quantifying another, and working to quantify the size of both errors in recent upper ocean heat content estimates (Willis et al., 2007b, c). In addition, the effects of sparse historical in situ ocean temperature sampling patterns on global integrals of upper ocean heat content changes were investigated (Lyman and Johnson, 2007). Yearly ocean heat content maps were made by combining in situ temperature profiles with sea surface height anomalies from satellite altimeter data for 1993 through 2006 (Johnson et al. 2007a). Sea surface salinity maps were made for 2005 and 2006 (Johnson and Lyman, 2007).

We detected one instrument error early in CY2007 in the process of analyzing ocean heat content anomalies. Incorrect pressures were ascribed to otherwise valid temperature and salinity data in a small subset of Argo floats, deployed mostly in the Atlantic Ocean. In terms of ocean heat content, the error introduced a large cold bias in a small fraction of Argo float data. The error is fully correctable for most of the affected floats and approximately correctable for the remainder. As of the writing of this report, the erroneous Argo float data had almost all been recently corrected. However, for heat content analyses published earlier in the year (Johnson et al., 2007a), the worst of the erroneous data were simply removed from the data set.

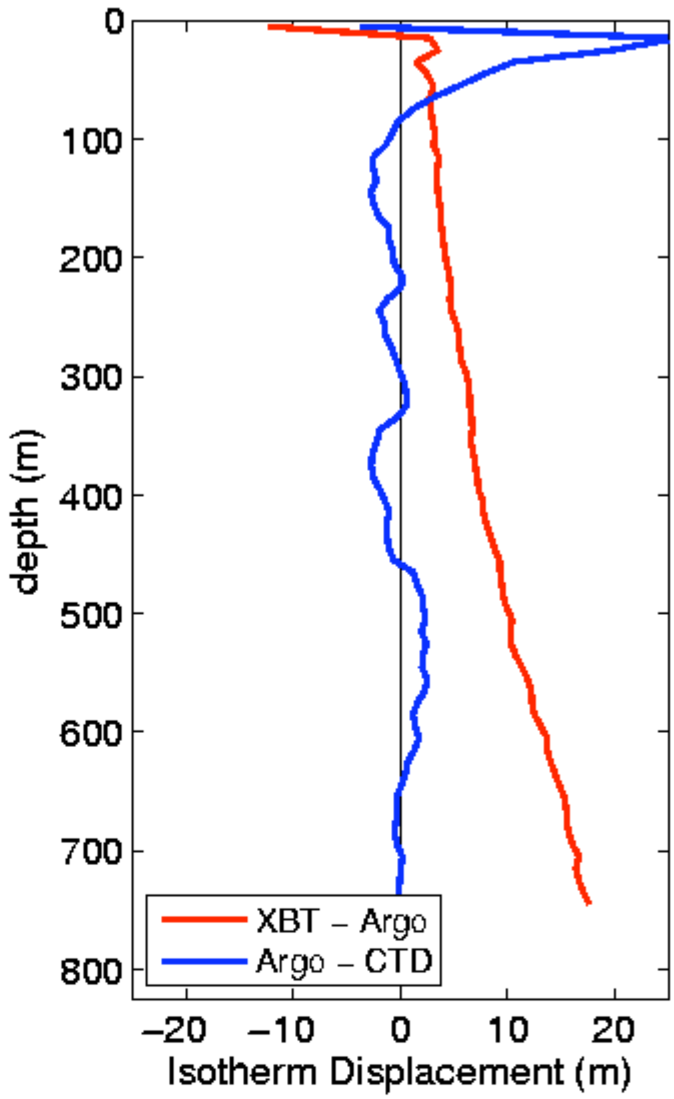

Figure 1. Depth errors due to XBT fall rate equation errors inferred from the median difference between isotherm displacements computed from 23,400 nearby XBT and Argo pairs collected between Jan. 1, 2003 and Dec. 31, 2006 (red line). The median difference between isotherm displacements computed from 2,000 nearby CTD and Argo pairs collected between Jan. 1, 2000 and Dec. 31, 2006 (blue line) is also computed excluding

all floats with known incorrect pressure data. Positive displacements reflect deeper isotherms, hence a generally warm bias. Figure after Willis et al. (2007c).

The other error is a smaller but more prevalent warm bias in eXpendable BathyThermograph (XBT) data. This error came to light after Johnson et al. (2007a) had been completed and appears to arise from variations in XBT fall rate (e.g. Figure 1). XBT fall rate equations are used to infer depths, which can be biased if there are errors in the fall rate equation parameters. While all the factors that cause this error are not known, the fall rates appear to vary with XBT model and date of deployment. For 2003-2006, this error resulted in erroneously deep report of XBT depths on the order of 2% (Figure 1; Willis et al. 2007c). A correction noting the detrimental effect of both of these errors on earlier results has been published (Willis et al, 2007b), and further analysis quantifying the significant effects of these errors on global integrals of upper ocean heat content has been submitted for publication (Willis et al., 2007c). Analyses of XBT biases over the entire historical record presently underway suggest significant interannual variations in XBT fall rates. These variations are very likely to have significant ramifications for accurate estimates of upper ocean heat content anomalies. It will take some time and effort to correct for this problem.

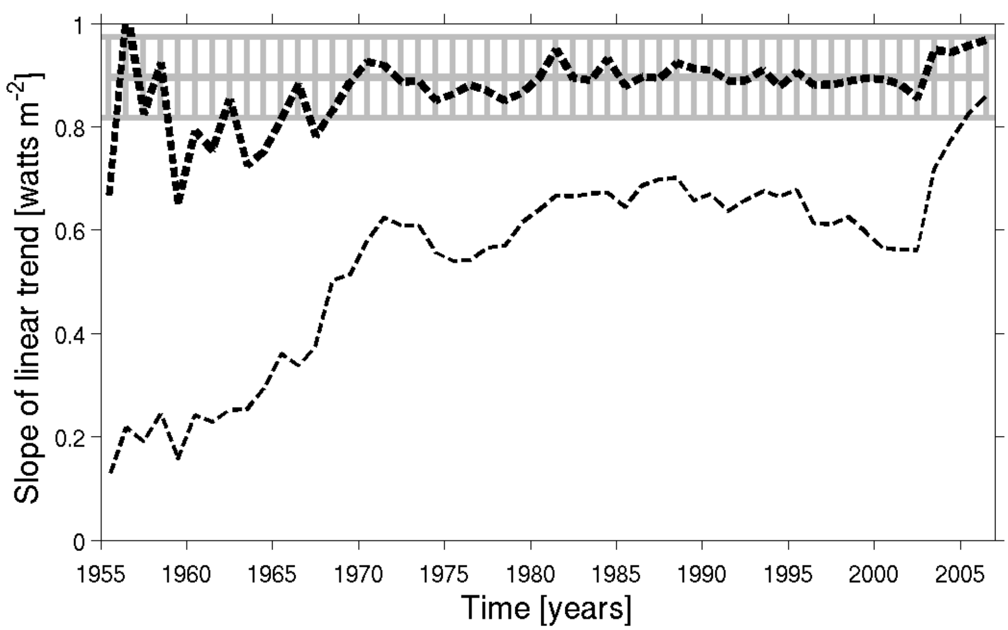

Figure 2. Warming trends of a synthetic upper ocean heat content record created from satellite altimetry data for the 13-year period from 1993 through 2006 calculated using the full record (grey line with error bars) and by resampling the 13-year record using each year's data distribution from 1955 through 2006 from both simply integrating the resulting objective maps (thin dashed line) and estimating representative integrals (thick dashed lines). Figure after Lyman and Johnson (2007).

Sparse in situ temperature profile distributions in pre-Argo years can also create difficulties in estimating global integrals of upper ocean heat content anomalies. An assumption used often in creating global integrals of this quantity is that unsampled regions have zero anomaly. Objective maps generally build in this assumption by increasingly relaxing back to a climatological mean value at locations and times where data coverage is increasingly sparse. We compared results using this assumption (that we term the integral of the maps) to results using another one: that unsampled regions have an anomaly equal to the spatial average of sampled regions in any given year (that we term the representative integral; Lyman and Johnson, 2007).

To do these comparisons quantitatively we developed a methodology to estimate the fractional area for which an objective map will replicate a globally uniform anomaly for any given data distribution, noise to signal ratio, and correlation function (Lyman and Johnson, 2007). We also used appropriately scaled set of high temporal and spatial resolution sea-surface height anomaly maps from 1993 – 2006 as a proxy for a fully sampled upper ocean heat content record. We resampled each year of this proxy using in situ sampling patterns for every year from 1955 – 2006. We compared how well the 13-year trend in the global integral of the fully resolved proxy was recreated for integrals based on objective maps of the proxy resampled for any given year's historical sampling pattern under the two different assumptions (Fig. 2). There are at least four significant conclusions. The historical sampling distributions for years prior to 1967 are inadequate for computing global integrals with confidence using either method. Also, estimates of global integrals of upper ocean heat content anomalies from integrals of the maps are likely to underestimate trends in global upper ocean heat content, especially early in the record. Representative integrals appear to do good a job of reproducing the actual trend. Finally, only in the last few years of the record, with Argo reaching near-global coverage, do the two methods agree within uncertainties.

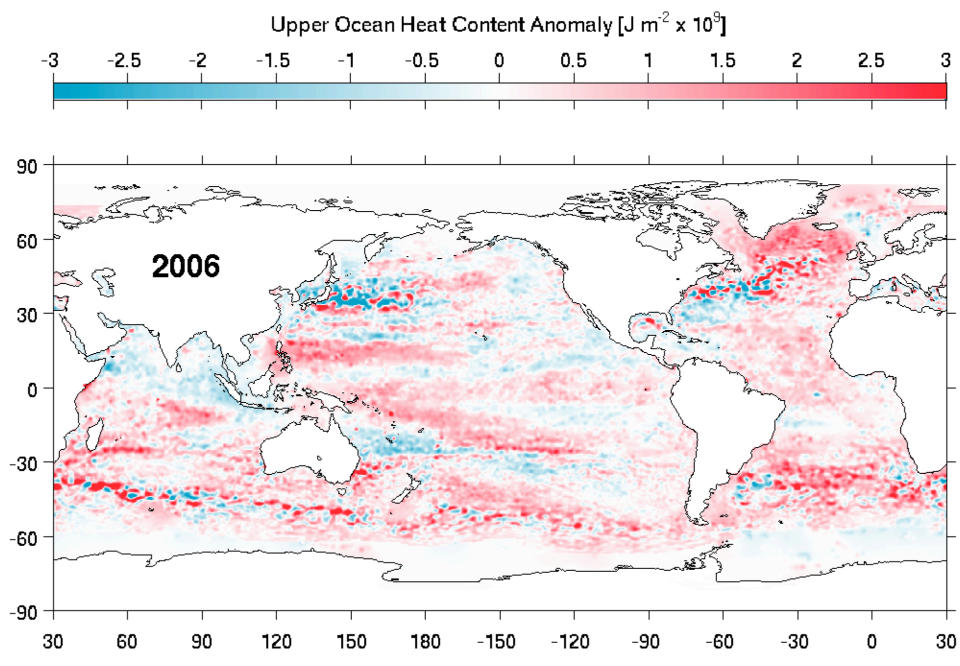

Figure 3. Combined satellite altimeter and in situ ocean temperature data upper (0 – 750 m) ocean heat content anomaly OHCA (J m^{-2}) map for 2006 (top panel) analyzed following Willis et al. (2004), but relative to a 1993 – 2006 baseline. Figure after Johnson et al. (2007a).

In addition to these investigations, we updated maps (e.g. Fig. 3) of annual upper (0-750 m) ocean heat content primarily for the ice-free portions of the globe from 1993 through 2006 combining in-situ and satellite altimetry data (following Willis et al. 2004) to better resolve smaller (sub-gyre) scale spatial variability over shorter (year-to-year) time-scales for the 2006 State of the Climate Report (Johnson et al., 2007a). The analyses were discussed in that report, and those discussions are not repeated here. While the Argo float profile data with serious pressure biases were removed from these estimates, no correction was made for XBT fall rate errors, which were not well known at the time.

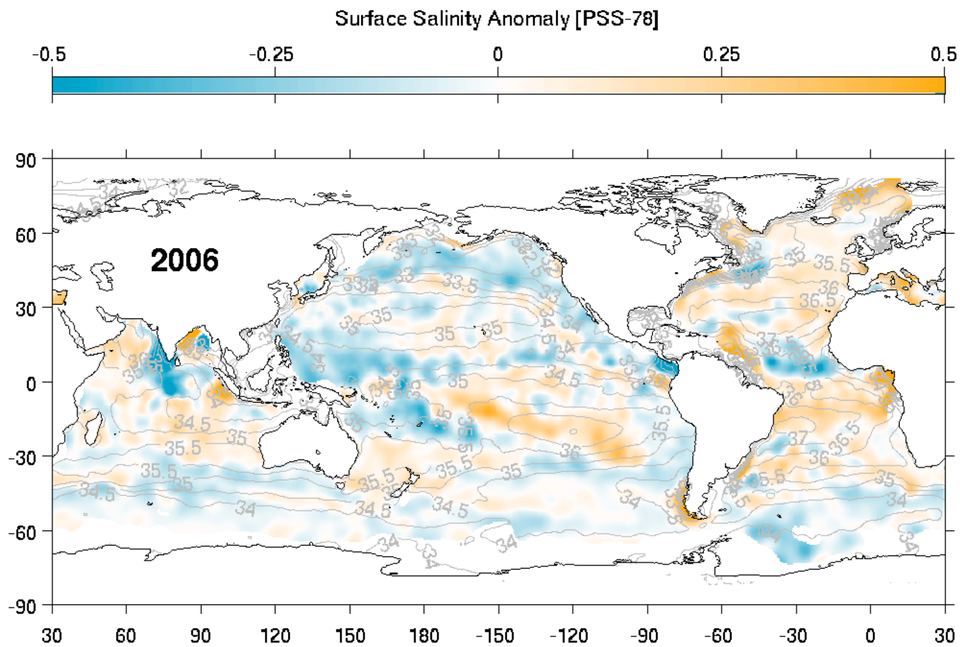

Figure 4. Map of the 2006 annual surface salinity anomaly estimated from Argo data [colors in PSS-78] with respect to a climatological salinity field from WOA 2001 [gray contours at 0.5 PSS-78 intervals]. White areas are either neutral with respect to salinity anomaly or are too data-poor to map. While salinity is often reported in practical salinity units, or PSU, it is actually a dimensionless quantity reported on the 1978 Practical Salinity Scale, or PSS-78. Figure after Johnson and Lyman (2007).

Finally, we began producing annual average maps of Sea-Surface Salinity (SSS) anomalies with respect to the World Ocean Atlas 2001 Climatology for the 2006 State of the Climate Report (Johnson and Lyman, 2007). These maps (e.g. Fig. 4) were only possible for 2005 and 2006, when Argo provided near-global coverage of SSS data. Again, the analyses were discussed in that report, and those discussions are not repeated here.

Manuscripts related to this project that were published or submitted for publication in FY2007 are listed below. The project web page is http://oceans.pmel.noaa.gov/.

FY2007 Publications and Reports:

Aagaard, K., T. J. Weingartner, S. L. Danielson, R. A. Woodgate, G. C. Johnson, and T.

E. Whitledge. 2006. Some controls on flow and salinity in Bering Strait. *Geophysical Research Letters*, **33**, L19602, doi:10.1029/2006GL026612.

Johnson, G. C., and J. M. Lyman. 2007. Global Oceans: Sea Surface Salinity. In State of the Climate in 2006, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **88**, **6,** S34-S35

Johnson, G. C., J. M. Lyman, and J. K. Willis. 2007a. Global Oceans: Heat Content. In State of the Climate in 2006, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **88**, **6**, S31-S33.

Johnson, G. C., J. M. Toole, and N. G. Larson. 2007b. Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *Journal of Atmospheric and Oceanic Technology*, **24**, 1117-1130.

Lyman, J. M, and G. C. Johnson. 2007. Estimating global upper ocean heat content despite irregular sampling. *Journal of Climate*, submitted.

Lyman, J. M., G. C. Johnson, and W. S. Kessler. 2007. Distinct 17-day and 33-day tropical instability waves in subsurface observations. *Journal of Physical Oceanography*, **37**, 855-872.

Willis, J. K., D. P. Chambers, and R. S. Nerem. 2007a. Closing the Globally Averaged Sea Level Budget on Seasonal to Interannual Time Scales. *Journal of Geophysical Research - Oceans*, submitted

Willis, J. K., J. M. Lyman, G. C. Johnson, and J. Gilson. 2007b. Correction to "Recent cooling of the upper ocean". *Geophysical Research Letters*, **34**, L16601, doi:10.1029/2007GL030323.

Willis, J. K., J. M. Lyman, J. M., G. C. Johnson, and J. Gilson. 2007c. In situ data biases and recent ocean heat content variability. Geophysical Research Letters, submitted.